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# EXPLORER XII SATELLITE INSTRUMENTATION FOR THE STUDY OF THE ENERGY SPECTRUM OF COSMIC RAYS


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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

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This report describes the signal conditioning and programming processes required to digitize, store, and read out the data from the various detectors used in cosmic ray instrumentation aboard the Energetic Particles Satellite, Explorer XII (1961 $\upsilon$). Excitation of the sensors by particles produced signals which were subcommutated in a multiplexing system separate from the one used in the satellite telemetry system. Two storage systems (15- and 512-bit capacities) and the programming method used to process the data from three separate detectors are described.

CONTENTS

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## INTRODUCTION

The Energetic Particles Satellite, Explorer XII (1961 $\upsilon$) was launched into a highly eccentric orbit on August 16, 1961. The major scientific objective was the study of energetic particles and magnetic fields in the vicinity of the earth up to a distance of 12 earth radii. The aim of the cosmic ray experiment was to study the energy spectra and time variations of both the galactic cosmic ray protons and particles of solar origin. To implement the cosmic ray experiment, three detector systems were designed: a double-scintillation telescope, a single-crystal scintillator, and a Geiger-Müller (GM) telescope. Briefly, the function of the three detector systems in the cosmic ray experiment were as follows:

*Double-Scintillation Telescope.* Two plastic scintillators (and associated photomultipliers) were used to form a double-scintillation telescope. The photomultipliers looked individually at the two scintillators. However, the output from only one of these photomultipliers was analyzed and stored only when a coincident pulse occurred from the other photomultiplier. When these conditions were met, the output of the single photomultiplier was processed by a 32-channel pulse-height analyzer (PHA). It gave the differential energy spectrum of protons from 100 Mev up to 500 Mev.

*Single-Crystal Scintillator.* A single, *thin,* (0.5 $gm/cm^2$) cesium-iodide crystal and a photomultiplier made up the single-crystal scintillator. The pulse output from the photomultiplier caused by excitation of the crystal was processed and stored in an eight-level integral PHA. This analyzer used a single 15-bit storage system with separate storage and readout cycles for eight different threshold levels.

Inflight calibration of this detector system was achieved with a small plutonium alpha source attached to the cesium-iodide crystal. This small source gave a well defined line spectrum at 3.5 Mev which also contributed a few counts per second to all channels from 1 through 4. This system extended the energy spectrum measurements for protons to a lower limit of 2 Mev.

*National Academy of Sciences, Senior Post-Doctoral Fellow.

*Geiger-Müller Telescope.* Two pancake-type halogen-filled Geiger-Müller counters and a coincidence circuit made up the GM telescope. Information (pulses) of single events were stored and read from one of these counters. The coincident circuit provided a pulse output only when both counters were energized (ionized) simultaneously. Coincident and single events were stored and read in the 15-bit accumulator along with the eight-level PHA in time sequence.

The minimum threshold of proton energy for single events was about 27 Mev. Protons above 70 Mev were required to produce a coincident event.

## GENERAL

The information from each of the three detector systems was conditioned and programmed in the cosmic ray logic package and then encoded for two of the information channels into the spacecraft telemetry system. Figure 1 shows the location in the spacecraft of the sensors and electronics of the cosmic ray experiment. A more detailed view of the entire instrumentation is shown in Figure 2; in

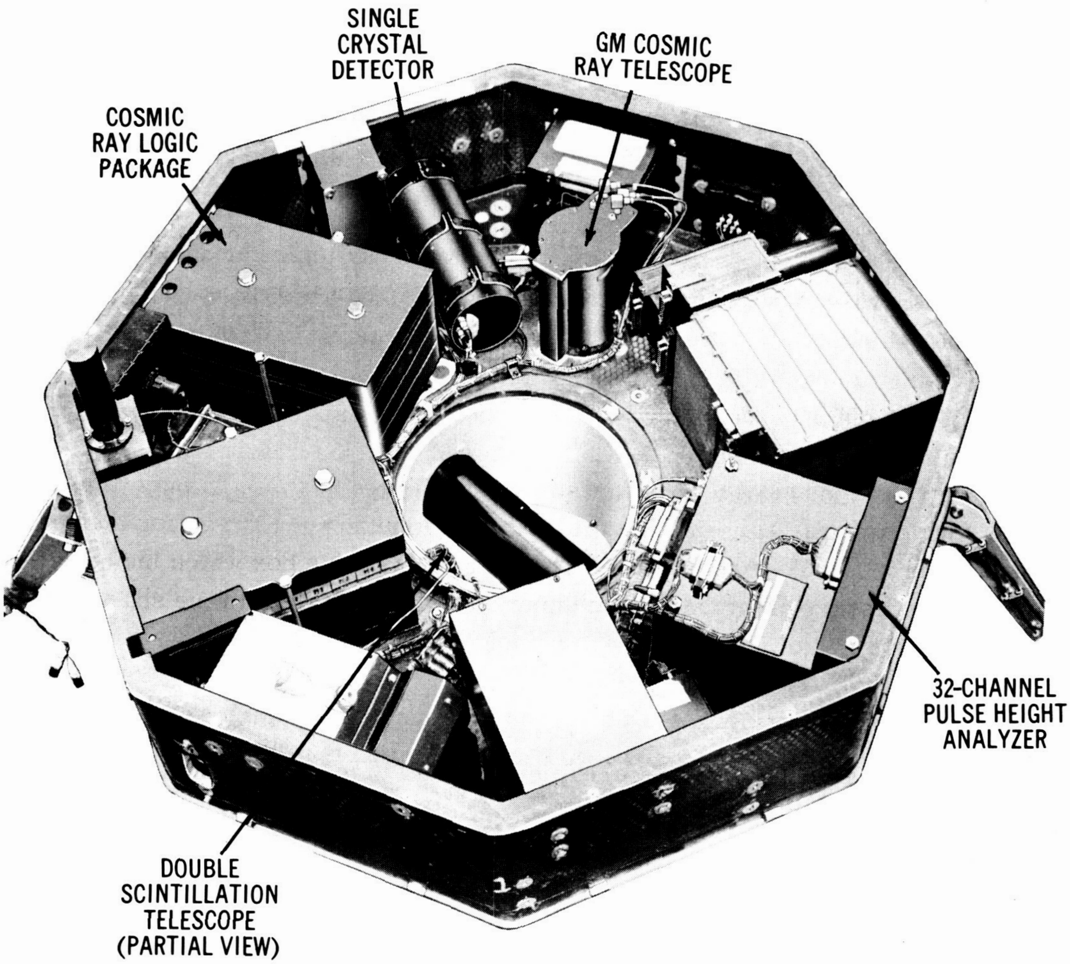



Figure 1—Location of the cosmic ray instrumentation in the Explorer XII satellite.

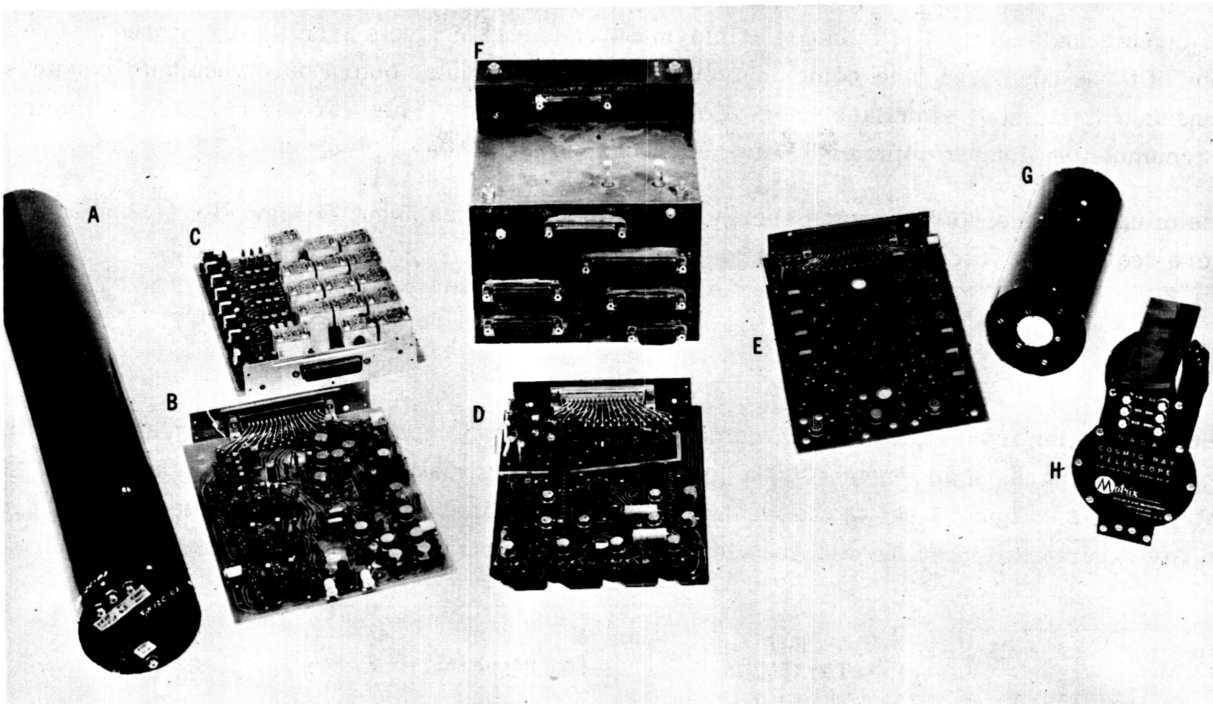



Figure 2—Detailed view of the entire instrumentation: A is the double-scintillation telescope; B, C, D, E are the circuit boards from the cosmic ray logic package; F is the 32-channel pulse-height analyzer; G is the single-crystal scintillator; H is the Geiger-Müller-counter telescope.

this illustration the four circuit boards that make up the cosmic ray logic package are shown individually.* Figure 3 is a general block diagram of the entire cosmic ray instrumentation.

## COSMIC RAY LOGIC PACKAGE

The three detector systems gave four different outputs. Three of these outputs (the GM single, GM concident, and single crystal) time-shared the 15-bit accumulator. Storage for the double telescope data was provided in the 32-channel PHA. The cosmic ray logic box which included the 15-bit memory provided the necessary programming to dump these stored data into the spacecraft telemetry system.

Because of the two different memory systems, and the manner in which they were used, it was necessary to provide special multiplexing and identification so that the data could be read as a series of 3-bit words from the respective memories (Reference 1).

*Prior to assembly as the cosmic ray logic package, each board was encircled with an aluminum strap and then potted with foamed polyurethane. The entire package was formed by stacking the four potted cards together with a top and bottom plate and a riser to support the cable harness.

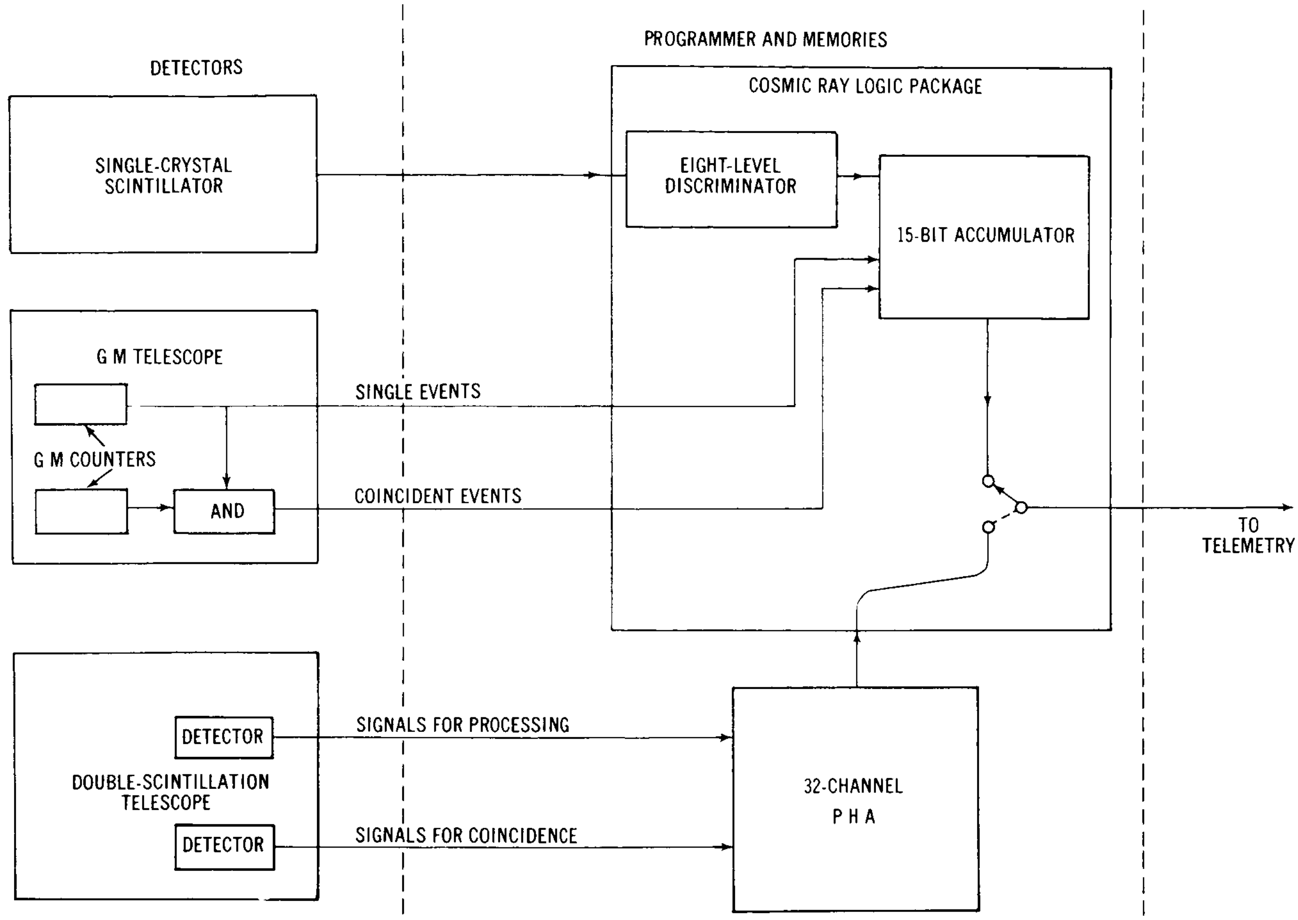



Figure 3—General block diagram of the cosmic ray instrumentation.

## TELEMETERING SYSTEM

A PFM telemetering system was used on Explorer XII (Reference 2). A similar PFM system has been used on a number of satellites, including Vanguard III (1959 $\eta$), Explorer VIII (1960 $\xi$1), and Explorer X (1961 $\kappa$). This PFM system was designed with 16 tone bursts, each 10 milliseconds in duration with a separation of 10 milliseconds. Information was telemetered as frequency modulation of each tone burst, obtained from subcarrier oscillators each having a frequency range from 5 to 15 kc. The 16 tone bursts carried time-shared information of 16 separate channels which made up a telemetry frame having a time-per-frame rate of $16 \times 0.02 = 0.32$ second. To accommodate more information, the frames were sequentially subcommutated 16 times generating a format of $16 \times 16$ bursts (channels).

Depending on the type of subcarrier oscillator used for each channel, either analog or digital information could be telemetered. The experiments that used digital oscillators processed three bits at a time and had a maximum bit rate of 150 bits per second (3 bits per 0.020 second). The analog oscillators could be read out by a ground data reduction system to an accuracy of 1 percent; the maximum bit rate for analog information was therefore nearly 300 bits per second. The average bit rate from the entire telemetering system (analog and digital information rates combined) was about 250 bits per second. The information rate for each experiment was less than this, because each channel shared time each frame with every other channel. For instance, the cosmic ray experiment was assigned two channels (channels 3 and 11) and used a single digital subcarrier oscillator. Because two channels were assigned to this experiment, six bits of information were read out each frame (six bits every 320 milliseconds).

## PROGRAMMING

To best use the data bit rate of the telemeter and best serve the purpose of the experiment, the read and storage time of the various sensors using the 15-bit accumulator were programmed so that there would be five telemeter frames of storage (1.6 seconds) followed by three frames of readout (0.96 seconds). In an 80-frame sequence, 16 frames were used to store and read the output of the GM-counter telescope; 64 frames were used to store and read out all levels of the eight-level analyzer.

The 80-frame sequence was repeated 12 times—a total of 960 frames. During this same time interval, information from the double-scintillator telescope was continuously stored in the 512-bit memory of the 32-channel PHA. After 960 frames, a continuous readout of this memory started; it lasted for two and a half complete readout cycles—320 telemeter frames. The first readout cycle was a non-destructive, the second was destructive and cleared the memory; the half-cycle was to confirm that the memory was cleared by the destructive readout. No data were stored during the 320- frame readout cycle. During the 960-frame period both the eight-channel and the 32-channel PHA stored information. Thus the sampling of data from all of the sensors was done during the same time interval; this feature was very useful in the interpretation of the data.

To provide the long subcommutation intervals required for this experiment, a special programmer (Figure 2B and Figure 6) using flux-stepping magnetic counters (trade name Incremags) was developed by the General Time Corporation. The programmer divided the 16-frame ($8 \times 8$) signal supplied from the telemetry encoder. The required count-down was achieved by using divisors of 5, 4, and 4 in the three respective magnetic stages. From this count-down, the frame sequences of 80, 320, and 960 frames were derived. The B2 bistable (Figure 4) further divided the 80-frame sequence into a 16-frame and 64-frame gating signal which was used to separate the GM-counter telescope data from that of eight-level analyzer. Gates G1 and G2 were used to subcommutate the 16-frame interval, thus separating the coincident data from the single events detected by the GM counters.

The B1 bistable, which gated the input to the 15-bit accumulator, was set and reset by sync signals directly from the telemetry encoder, and divided each eight-frame sequence into five frames for storage and three frames for readout. This same frame pattern was used by the eight-level PHA on each level, and the GM counter on single and coincident events. A three-frame read period was needed to read the 15 bits in the accumulator plus the three bits that identified each of the eight levels of the integral PHA. The assigned telemetry channels (3 and 11) readout a total of 18 bits in three frames after each storage interval of five frames.

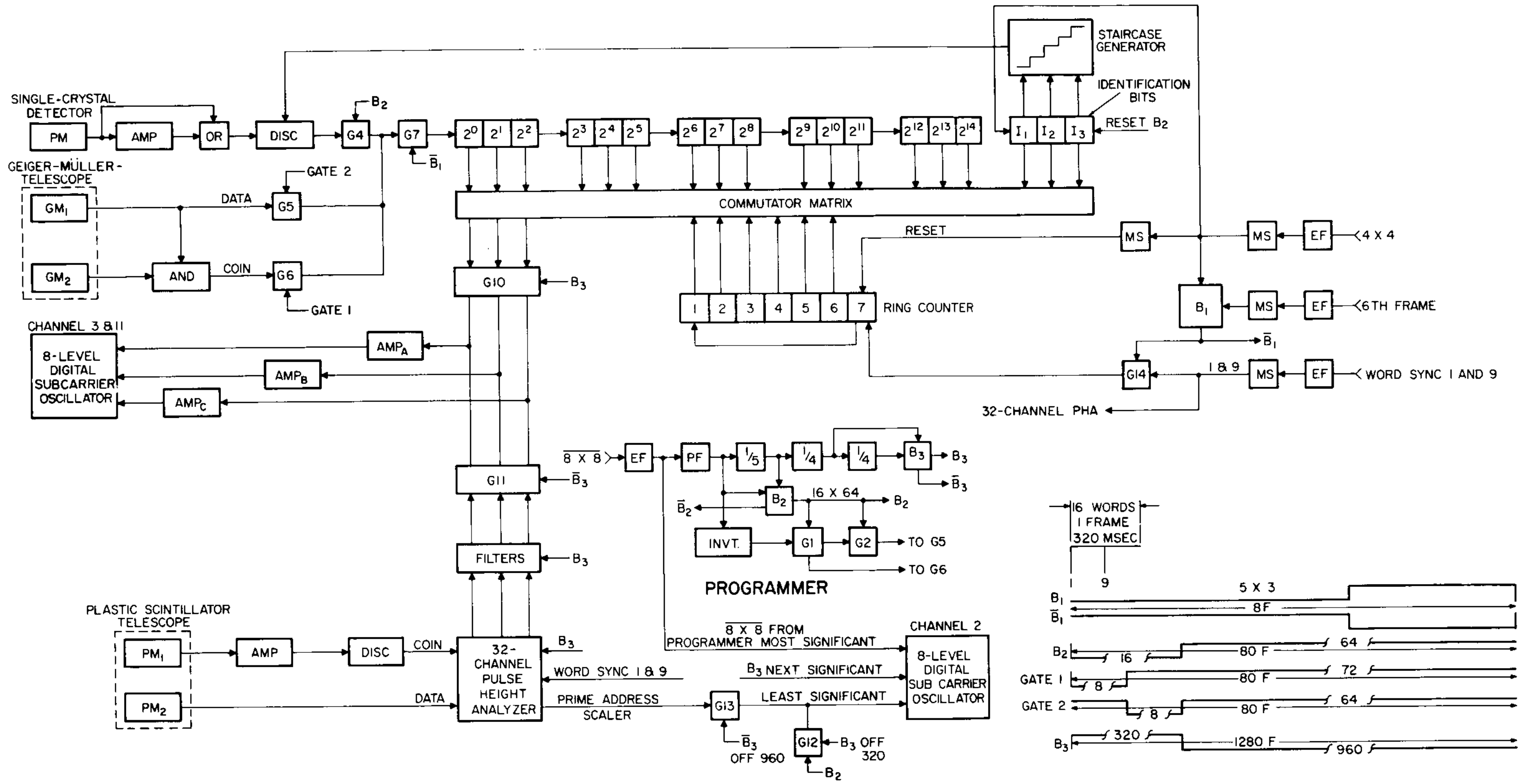
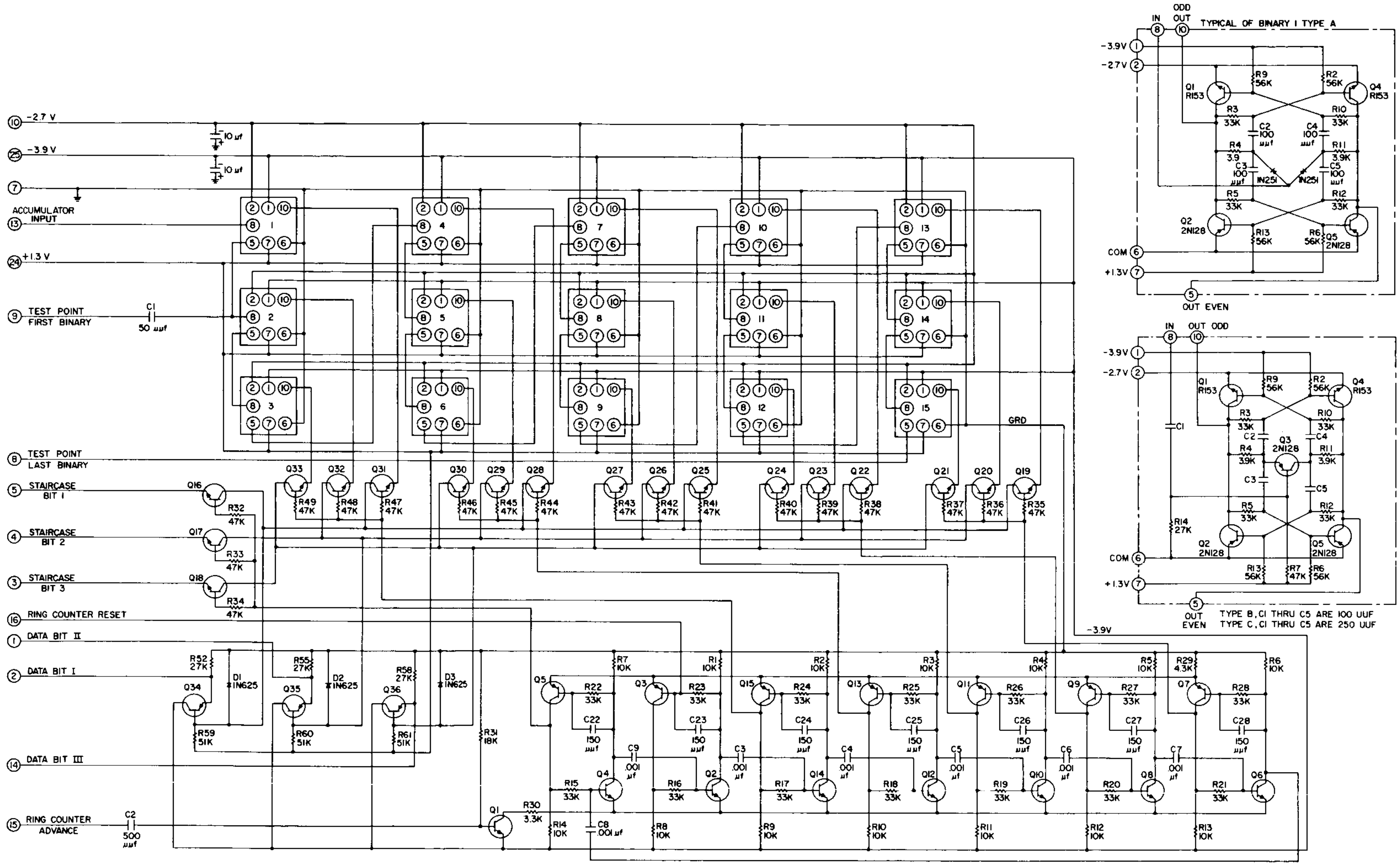



Figure 4—Detailed block diagram of the cosmic ray instrumentation.




NOTES:
1. R153 - Q1,Q2,Q4,Q6,Q8,Q10,Q12,Q14,
2. 2N1122A-Q34,Q35,Q36
3. 2N128 - Q3,Q5,Q7,Q9,Q11,Q13,Q15
4. BINARIES 2 THRU 6 ARE TYPE B
5. BINARIES 7 THRU 15 ARE TYPE C
6. 2N703 - Q19 THRU Q33
7. 2N167A - Q16,Q17,Q18

Figure 5—Circuit diagram of the 15-bit accumulator.

The commutator matrix was gated from a seven-position ring counter. Six positions were active and commutated the six 3-bit words during the active readout time; the seventh position was a rest position which disconnected the commutator during the five-frame storage period.

The three-wire gates, G10 and G11, operated alternately during the 320- and 960-frame sequence which provided the alternate readout of the 15-bit and the 512-bit memory.

Channel 2 in the telemetering system provided all the identification necessary for data reduction of the 15-bit memory and also identified the read and storage mode of the 32-channel PHA. Further identification was provided during readout of the 32-channel PHA; the end of each channel was identified by one data bit in each telemetered 3-bit word.

## SINGLE-CRYSTAL SCINTILLATOR AND ITS ASSOCIATED MEMORY

To extend the lower limit of the energy spectrum of protons, the output of the single-crystal scintillator was processed by the eight-level integral analyzer.

From the total energy loss measurements, an integral energy spectrum of protons in the range from 2 to 9 Mev was obtained; from the rate of energy loss measurements, an integral energy spectrum was available for protons above 14 Mev.

## 15-BIT ACCUMULATOR

Figure 2 shows the circuit board (C) containing the 15-bit accumulator (memory), the ring counter and the matrix used to process the data from the single-crystal detector and the GM-counter telescope. The 15-bit memory was made up of 15 binary scalers arranged for nondestructive readout. Physically, each scaler is a separate module on the printed circuit board. The scalers were efficient complementary symmetrical bistable stages and used five germanium transistors (Figure 5). Similar units have been used in many circuits developed by Goddard Space Flight Center; some of the more recent versions used silicon transistors which gave superior performance over the germanium versions.

The commutator matrix consisted of transistors Q16 through Q33. The gates were controlled three at a time from six stages of the ring counter. The ring counter was advanced by a signal from the telemetry encoder each time the encoder samples channels 1 and 9.

Since the memory was read out from the time-multiplexed telemeter when channels 3 and 11 were sampled, the matrix gates were set up 40 milliseconds earlier. To maintain synchronization with the encoder for the five-frame store and three-frame read sequence, the ring counter advance pulses were interrupted by gate G14 during the five-frame store period. This left the right counter in position #7 (an open circuit condition) for the duration of the five frames. This is shown in the detailed block diagram (Figure 4) and circuit diagrams Figures 5 and 7. As an added assurance of synchronization, a reset signal (each eight frames) restored the ring counter to its rest position before every readout sequence.

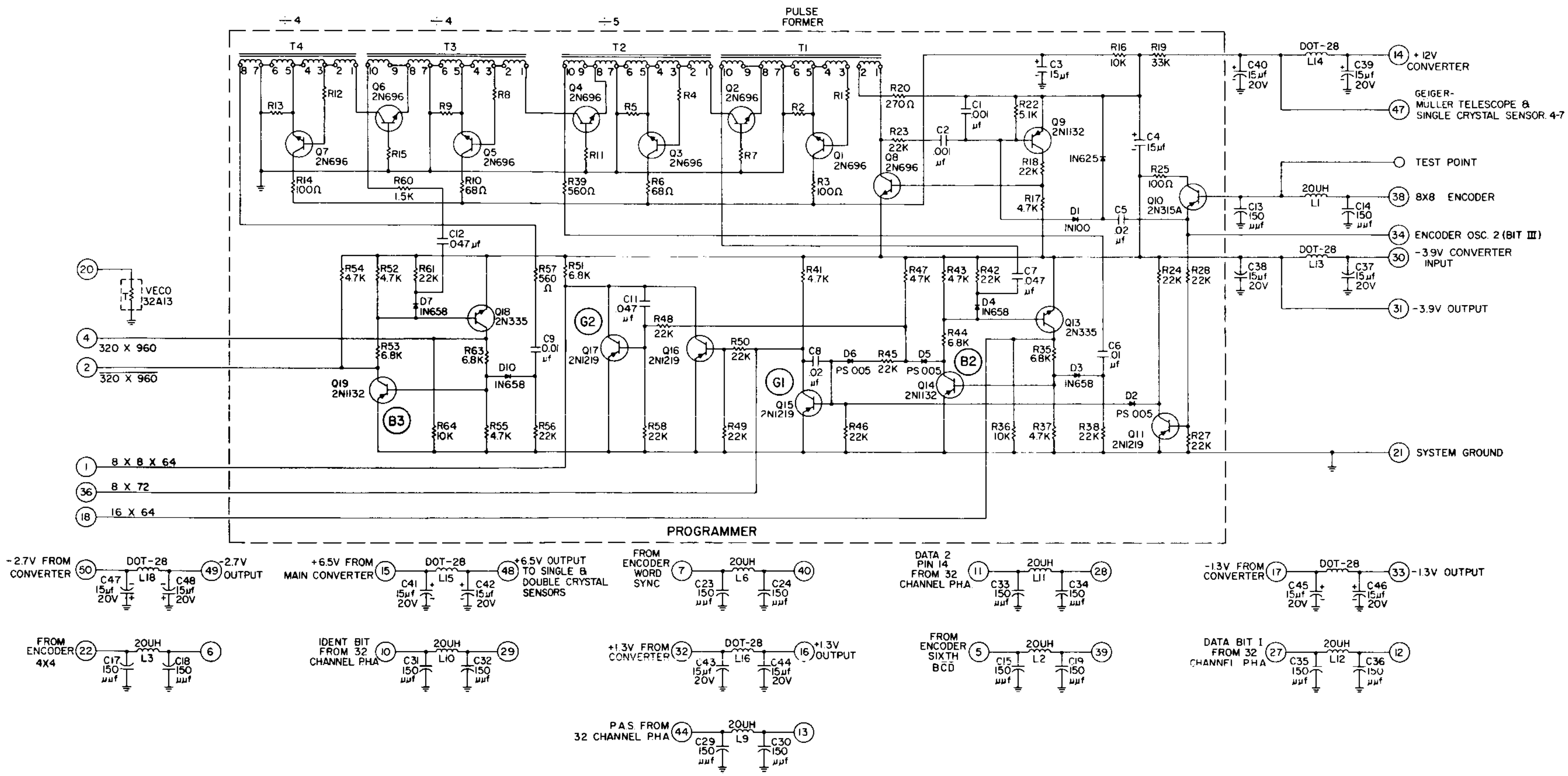


Figure 6—Circuit diagram of the programmer.

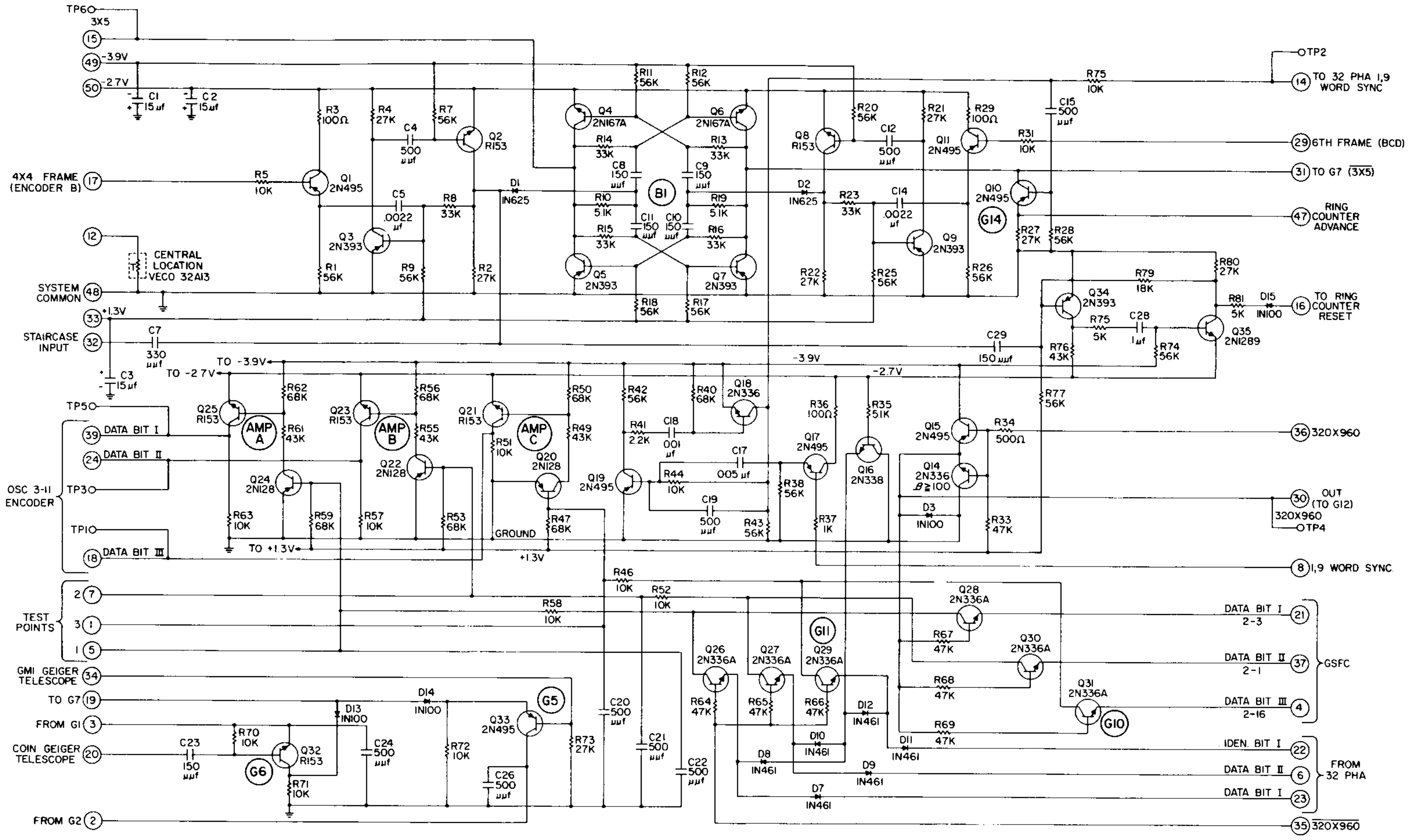



Figure 7—Circuit diagram of miscellaneous gates.

## EIGHT-LEVEL PULSE-HEIGHT ANALYZER

The eight-level analyzer was similar to the one reported by the authors in 1960 (Reference 3). It was a threshold-integral type which stored all pulses above the discriminating level. The analyzer used a staircase generator to bias an amplitude discriminator at eight increasing levels. Its principal parts were an input amplifier, a staircase voltage generator, a discriminator, and an output monostable multivibrator (Figure 8).

The input amplifier was used to extend the sensitivity of the analyzer by amplifying millivolt signals due to ionization corresponding to 100-kev energy loss. At the second discriminating level and above, the input amplifier was unnecessary and was turned off by switch Q41; this conserved some power as well as assured that there was no contribution from large amplified pulses at the second level of discrimination.

Sensitivity for the second level and above was adjusted with the 5-kilohm potentiometer in emitter-follower Q16. The input amplifier had a fixed voltage gain of approximately 100 and ordinarily any small gain change required at the first level was accomplished by an increase or decrease in an integrating capacitor at the output of the photomultiplier. This capacitor and an emmiter-follower were mounted in the tubular housing with the photomultiplier (Figure 2G). The staircase voltage used to bias the discriminator to the eight levels was derived from three complementary binary stages. They functioned as double-pole switches which formed eight selective voltage dividers with three proportional resistors R95, R61, and R46 (Figure 8). The three bistables were driven as a binary counter from an eight-frame sync pulse which caused the staircase level to shift at the end of each five-frame and three-frame sequence; thus, storage and readout occurred at the same level. At the end of each eight-level sequence (64 frames), the binary scalers were reset by driving transistor Q38 OFF, and holding it OFF during the 16-frame sequence. This caused the three identifying bits to read zero during the GM telescope 16-frame sequence and insure that the next eight-level sequence of the analyzer began on the first of the eight levels.

Any pulse that passed the discriminator triggered a high-speed monostable multivibrator whose output was gated by G4 and G7 and stored by the accumulator. The monostable multivibrator and discriminator were designed so that pulses with repetition rates up to 200,000 pps could be processed. The overall stability of the staircase voltage and discrimination was within 5 percent from -20° to +50° C.

The read-store, five-frame and three-frame sequence, was derived from the set and reset action of the B1 bistable in Figure 7. The three-wire gates, G10 and G11, passed each three bits of information via the three saturating amplifiers on to the digital oscillator in the telemetry encoder. Gates G5, G6, and G14 were mounted on the same circuit board.

## 32-CHANNEL PULSE-HEIGHT ANALYZER

The analyzer was developed by Radiation Instrument Development Laboratories to be used as a spacecraft instrument for satellites and space probes in the study of energetic particles. Basically,

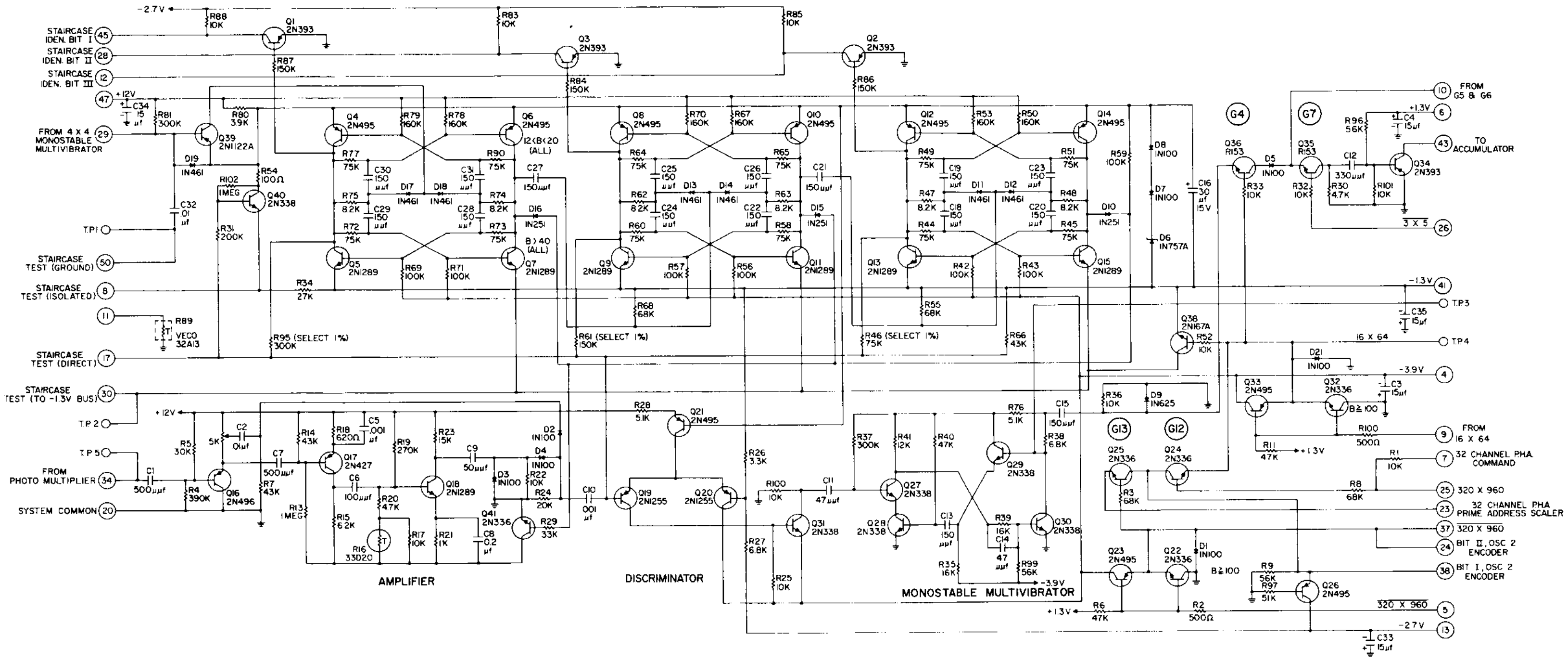



Figure 8—Circuit diagram of the eight-level pulse-height analyzer.

it was a simplified version of the more complicated laboratory types which have a greater channel capacity. It accepted incoming pulses from radiation detectors and analyzed them according to pulse amplitude by sorting pulses of equal or nearly equal amplitude into various channels. Each of the 32 storage channels had 16 bits; making the total storage capacity 65,526 counts in a single channel. The analyzer had a magnetic memory and contained nearly 300 transistors in all of its various circuits (amplifiers, analogue-to-digital converter, 500 kc crystal clock, gates, memory address, read, write, and other control circuits). Provision was made to store pulses in coincidence with the store and read mode under control of external signal. The readout of information could be made either destructive or nondestructive. The rate of readout for this experiment depended on trigger pulses supplied from the telemetering encoder.

The analyzer weight 5.5 pounds and was powered from a 2-kc 26-volt square wave at an average power of 0.75 watt.

Along with the double-scintillator telescope, the 32-channel PHA gave a differential energy spectrum for protons from 100 Mev up to 500 Mev. This upper limit resulted from the degradation of resolution caused by the Landau spread of energy loss in the crystal of higher energy protons.

The 32nd channel (the maxiumum energy loss channel) stored the number of protons detected in the range of 32 to 100 Mev. This channel also included the measurement of the flux of alpha particles. The peak due to the majority of minimum ionizing particles was used as an inflight calibration

Information was stored only when coincident events were detected from both photomultipliers in the double-scintillator telescope. One of the detectors supplied pulses directly from the output of the photomultiplier (via an emitter-follower); the output from the other photomultiplier was amplified and converted into a gate pulse of 2 microseconds in duration. These two signals were received by the 32-channel PHA and allowed the data pulses to be processed and stored by the analyzer only when the two signals were in coincidence. The double-scintillation telescope (A in Figure 2) contained, in addition to the plastic scintillation detectors and a high-voltage power supply, an amplifier and a monostable multivibrator.

## EIGHT-LEVEL DIGITAL SUBCARRIER OSCILLATORS

Each three bits of digital information was processed very simply and efficiently in the telemetry encoder by dc-coupling the voltage from three binary scalers into the subcarrier oscillator module. Each three bits of information were processed in ascending order, that is, by commuting the three bits of lowest order first in each 3-bit word. In each 3-bit word, the least significant, the next significant, and the most significant bits were consistantly commutated on the three lines indicated in Figure 9.

This type of multiple-magnetic-core digital oscillator was developed by D. H. Schaefer of Goddard Space Flight Center and was used on Explorer VIII and Explorer X. On Explorer X, one oscillator used five magnetic cores and handled four bits of digital information simultaneously by generating 16 discrete frequencies. A PFM telemetry system similar to that used on Explorer XII was used to transmit these discrete frequencies.

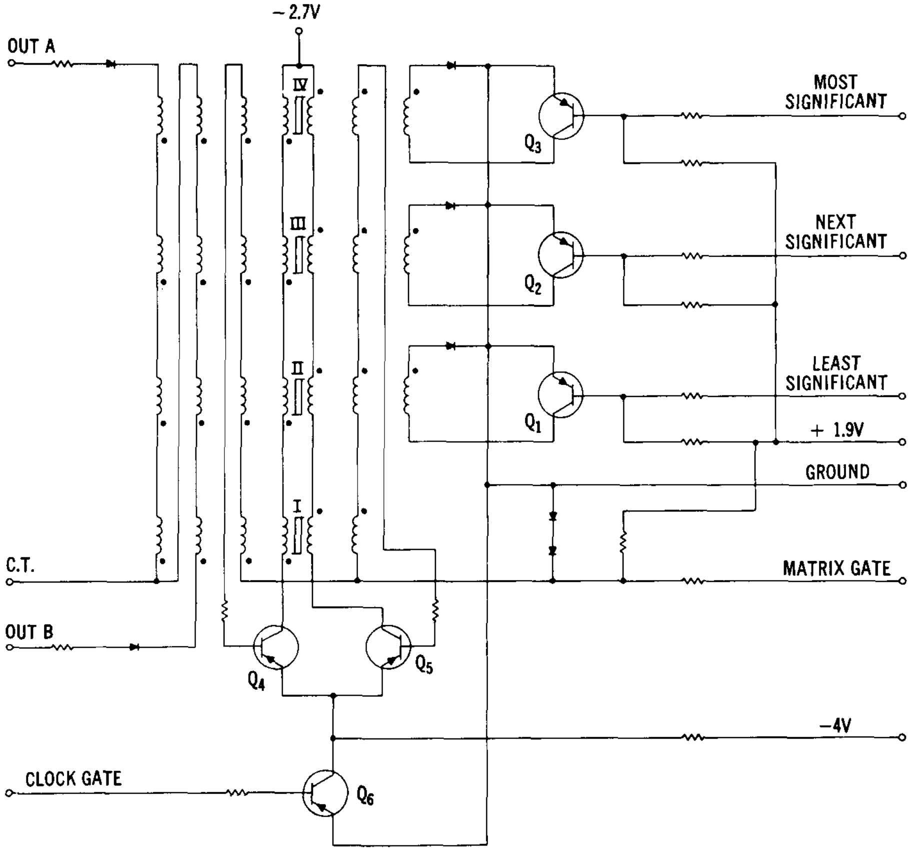



Figure 9—Circuit diagram of the eight-level digital subcarrier oscillator (5 to 15 kc).

The eight-level oscillators shown in Figures 9 and 10 were used on the Explorer XII satellite and the first United Kingdom (UK-1) satellite to encode all of the digital data. Basically this oscillator was a magnetic-coupled multivibrator which produced a frequency of oscillation, f, given by

$$f = \frac{E \times 10^8}{2N\left(\theta_I + \theta_{II} + \theta_{III} + \theta_{IV}\right)} , \tag{1}$$

where $\theta_I$, $\theta_{II}$, $\theta_{III}$, and $\theta_{IV}$ represent the total flux in maxwells for each of the saturating cores, the voltage E is constant, and the nominal number of turns on each core is constant. If the flux $\theta$ of any individual core was eliminated, there was a step change in frequency. Further, since the cores were chosen so that cores II, III, and IV stood in the ratio 1:2:4 the frequency could be changed in eight discrete steps by selection of the eight possible combinations of these three cores. Core I was not allowed to change so that when cores II, III, and IV were eliminated, the maximum frequency was determined by the value of flux $\theta_I$. The minimum frequency was determined when all the cores contributed to the total flux.

Figure 9 shows how transistor switches Q1, Q2, and Q3 were used to short-circuit a secondary winding on cores II, III, and IV and thus effectively eliminate these cores from the oscillator. The

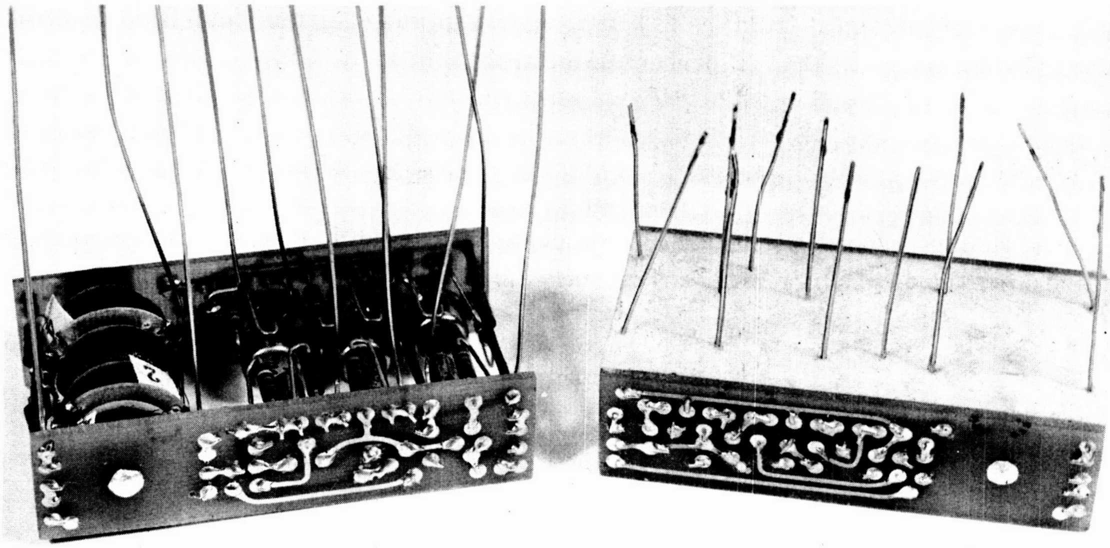


Figure 10—The eight-level digital oscillator before and after potting.

switches Q1, Q2, and Q3 were closed whenever any of the three input data lines reached a negative potential of 2 volts or more.

In this PFM telemetering system, it was convenient to control the oscillators by coincident commands, one from the telemetry encoder matrix and the other from the telemetry clock. The two gates clock and matrix, were provided for this purpose so that switching transistors Q4 and Q5 were biased ON during the blank-burst interval, and transistor Q6 was effectively shorted for one-half cycle of the clock period. Thus, a tone burst from a given oscillator could be keyed on for as many channels as were desired by supplying the appropriate turn-on signals to the matrix gate. For example, the cosmic ray instrumentation received turn-on signals from the matrix for both telemetry channels 3 and 11.

It was difficult to reproduce these digital oscillators because of the nonuniformity of the magnetic cores. To overcome this nonuniformity, adjustments were made in the number of turns on each individual core. For stability, careful selection of the magnetic cores, in addition to thermal cycling of the wound cores, improved the yield of acceptable finished oscillators. It was not surprising that some problems appeared in the manufacture of such devices, especially since the average accuracy of the eight discrete frequencies was required to be $\pm 2$ percent over a temperature range of $-10°$ to $+60°C$.

## RESULTS

The cosmic ray instrumentation as well as the other experiments aboard Explorer XII performed very satisfactorily until December 6, 1961, when the satellite stopped transmitting. As of this writing, the data transmitted from the satellite are still being reduced; already much valuable information has been obtained regarding solar events and galactic cosmic rays. At apogee (83,000 km), the signal-to-noise ratio of the signal from the 2-watt transmitter was such that real-time data reduction was accomplished for more than 90 percent of the time.

## ACKNOWLEDGMENT

The authors wish to acknowledge Dr. F. B. McDonald who began the cosmic ray experiment for this satellite and provided encouragement and direction for the instrumentation.

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